Space Radiation Effects and Hardness Assurance for Linear Integrated Circuits†

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Abstract

New effects that complicate the application of linear devices in space are discussed, including enhanced damage at low dose rate and proton damage, which cause permanent degradation. Transients produced by protons and heavy ions are also discussed.

Introduction

Linear integrated circuits based on unhardened commercial designs have been used in space systems for many years. However, several phenomena have been observed in radiation testing of linear circuits that make it far more difficult to use these devices with confidence in space than was apparent from the experience with older fielded systems. These include (1) dose rate effects, which result in more damage at the low dose rates used in space compared to high dose-rate characterization data; (2) proton displacement damage, which can cause more degradation to occur for some circuit types in space than indicated by tests with gamma rays; and (3) transients from heavy ions and protons which produce spurious signals that may disrupt circuit operation.

These effects are not new, but apparently did not cause problems in older systems. The reasons for this are twofold: first, most older spacecraft systems used very conservative designs which did not take into account the very significant effect of additional shielding provided by the spacecraft structure; and second, older linear integrated circuits were designed more conservatively, providing more internal circuit margin, particularly for lateral and substrate pnp transistors which are used along with high-gain npn transistors in the circuit design.

The trend towards smaller spacecraft with composite structure will reduce the amount of "extra" shielding in the spacecraft structure, lowering the design margin. Many new linear integrated circuits use more complex designs with tight electrical tolerances, have the ability to operate at very low voltage and low power, and are designed with considerably less margin for gain degradation of pnp transistors within the circuit. These factors make it necessary to reexamine radiation degradation and hardness assurance for linear integrated circuits.

Low Dose Rate Effects

A. *Experimental Observations*

The inherent sensitivity of many linear integrated circuits to dose rate was first noted in 1994 [1-4], and remains a somewhat confusing problem. The initial circuits that were evaluated were comparators with very simple input stages. Although far more degradation occurred at low dose rate than at high dose rate, the circuits remained functional even after relatively high radiation levels, provided the large increase in input bias current could be tolerated in the circuit application. Other key parameters such as input offset voltage and output drive were only slightly affected by the increased degradation of internal transistors at low dose rate.

Figure 1 shows how the input bias current of a basic op-amp, the LM158 responds to ionizing radiation at different dose rates. Approximately ten times more damage occurs under low dose rate conditions. Note that it is necessary to reduce the dose rate to the range of 0.001 to 0.005 rad(Si)/s in order to get the maximum amount of ten times worse damage. This requires special radiation facilities, along with time periods of several months to complete the irradiation.

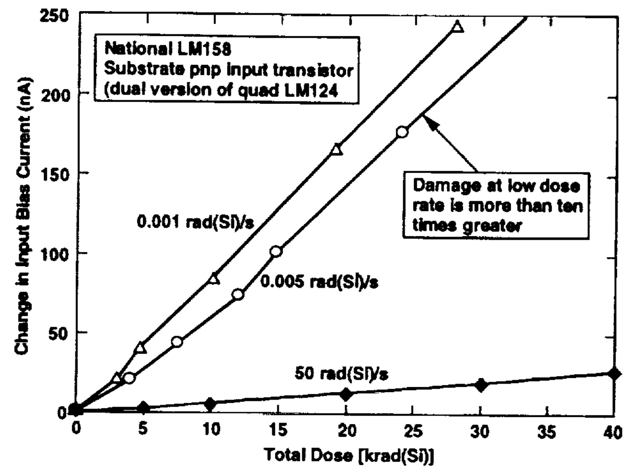

Figure 1. Effect of cobalt-60 irradiation at high and low dose rate on the LM124 op-amp (substrate pnp input transistor).

For some circuits, the effects of low dose rate are far more severe. One example is the OP-42 op-amp, originally recommended for use on the JPL Cassini system. The manufacturer's data sheet shows a typical change in input offset voltage of 3 mV at 1 Mrad(Si), which would appear to provide more than adequate margin for the Cassini mission [100 krad(Si)]. However, tests of this device at low dose rate showed extreme sensitivity to dose-rate effects, and it was removed from the program. Figure 2 shows the dependence of input offset voltage on total dose for the OP-42 at several dose rates. Note that changes in input offset voltage exceed 10 mV at about 10 krad(Si) at very low dose rate, a decrease in radiation hardness of about two orders of magnitude compared to test results at high dose rate that were used by the manufacturer to recommend the device for space applications. The very large change in input offset voltage makes it very difficult to use this device in most circuit applications.

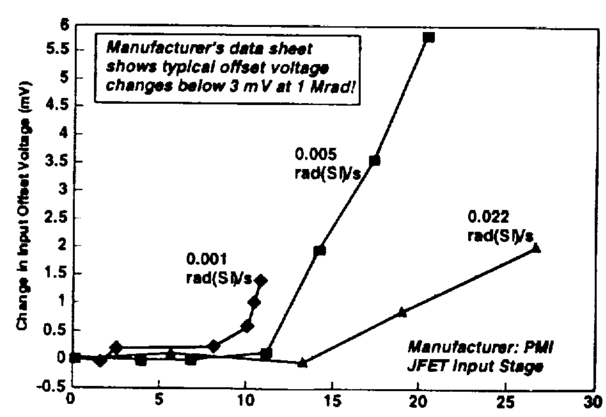

Figure 2. Radiation degradation of the OP-42 at different dose rates.

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Dose-rate effects depend on processing, and some manufacturers produce specific circuits which do not appear to have significant sensitivity to dose rate. However, nearly all linear manufacturers produce some part types where dose rate effects are important. Table 1 shows representative examples; note the variability for different device types. This makes the low dose-rate problem very difficult to deal with for commercial processes. It is impossible to make general conclusions about specific manufacturers because of the number of different processes that are used, and the difficulty of obtaining reliable information about changes in processes that are driven by the commercial marketplace.

Table 1. Dose Rate Sensitivity of Various Linear Devices

Manuf.	Device	Function	Dose Rate Sensitivity Minimal	Dose Rate Sensitivity Large
An. Dev.	LM111	Comparator	X	
An. Dev.	OP-42	Op-amp		X
An. Dev.	AD562	V-F conv.		X
An. Dev.	AD783	Sample/hold	X	
Nat.	LM111	Comparator		X
Nat.	LM108	Op-amp		X
Nat.	LM158	Op-amp		X
Nat.	LM137	Volt. reg.		X
LinTech	OP27	Op-amp		X
Lin Tech	RH1056	Op-amp	X	
Mot.	LM324	Op-amp		X
Mot.	LM111	Comparator		X

B. Hardness Assurance Considerations

Hardness assurance is a difficult problem for linear devices because tests at very low dose rates are time consuming and expensive, limiting the amount of data that is available; and the net effect on a *circuit* usually depends on the interaction of several different internal transistors, with different dose rate sensitivity. In many cases the latter factor causes the circuit failure mode to be different at high and low dose rates. This makes it impossible to judge how devices respond under low dose-rate conditions from tests at high dose rate. For example, the OP-42 op-amp in Figure 2 will operate satisfactorily at a total dose level that is 100 times greater at high dose rate compared to low dose rates in space. This does not imply that damage in internal transistors is 100 times greater; it is caused by the nonlinear dependence of internal circuit functions on transistor gain.

Several laboratories have noted that dose-rate effects are not always consistent for different lots of devices of the same type from a single manufacturer [5,6]. This makes it necessary to do periodic radiation evaluations of linear devices. It also affects the way that archival data in data banks can be used. Not only are there relatively few test results at low dose rate, but the magnitude of the damage at low dose rate can vary significantly between different lots.

High-temperature irradiation was first proposed by Fleetwood, et al. [1], and is part of new test standards [7]. By doing the irradiation at an elevated temperature at high dose rate it is possible to get nearly the same amount of damage in an experiment that takes only a few hours, eliminating the need to irradiate devices for long time periods. Figure 3 shows an example where this approach works well. In this case, the dose rate was reduced somewhat to determine the interdependence of dose rate and temperature on damage. By using a slightly lower dose rate (2-10 rad(Si)/s) it is possible to do the irradiations at a lower temperature, reducing the total test time to several hours.

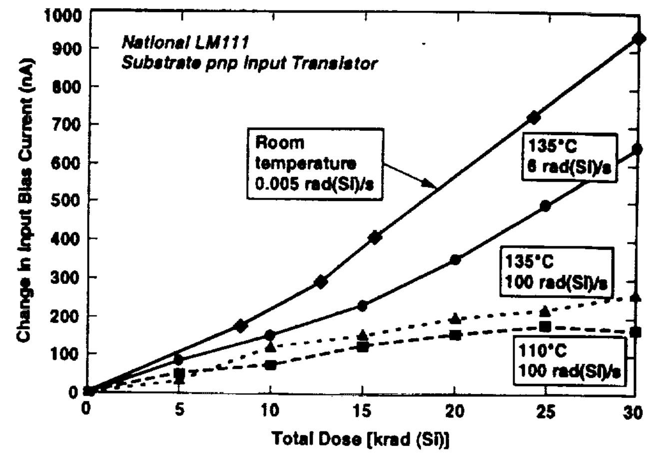

Figure 3. Comparison of low dose rate and elevated temperature irradiation for the National LM111 comparator

Unfortunately, the "appropriate" temperature to get equivalent damage is not the same for different devices and manufacturers. Witczak, et al. showed that different temperatures are required for lateral and substrate pnp transistors, even when they are from the same process [8]. Thus, "tracking" of damage in different types of transistors at low dose rate is not necessarily maintained during irradiation at elevated temperature. This is an inherent limitation of the elevated temperature approach.

Even more important is the selection of the temperature. If the temperature is too high it is possible for the damage to anneal, providing a misleading picture of device damage. Figure 4 shows an example for the LM324 [6]. In this case, using a temperature of 135 °C causes the large change in offset voltage to disappear.

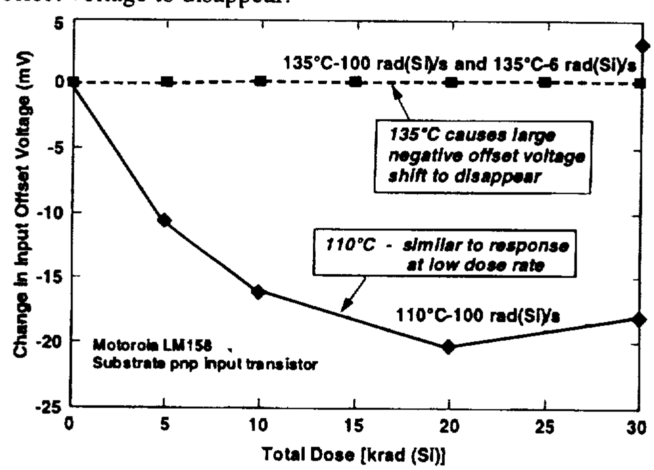

Figure 4. Effect of high temperature irradiation on the Motorola LM324 op-amp.

Although elevated temperature tests may not be exactly equivalent to irradiations of *circuits* at low dose rate, it may still be a useful way to identify devices with extreme dose-rate sensitivity. It is the only practical way to do tests on devices for applications at high radiation levels [> 100 krad(Si))] where tests at low dose rate are impractical.

An alternative approach which is useful for many systems with lower radiation levels is to do tests at two dose rates, approximately 0.005 rad(Si)/s and 100 rad(Si)/s. By comparing the results, it is possible to determine whether the circuit is sensitive to dose rate effects. Such tests can be completed in a period of about 4 weeks, and are easily done if a low dose-rate irradiation facility is available.

Advances in circuit design and processing have allowed manufacturers to develop devices with tighter specifications than older part types. For example, op-amps are available with input offset voltage of only 10 μV. Radiation degradation can cause such devices to degrade well beyond their specification limit at low levels, even though the basic circuit continues to function at much higher levels. If the design depends on operation to very close tolerances, then such devices can be extremely sensitive to radiation damage. Figure 5 shows an example for a 2.5 volt precision reference. The device exceeds specification limits at about 5 krad(Si) at low dose rate, but continues to operate with degraded specifications to about 50 krad(Si). This device is also sensitive to dose rate. Note the difference in the results at 0.005 and 0.01 rad(Si)/s. This illustrates the importance of doing low dose-rate tests at sufficiently low dose rates.

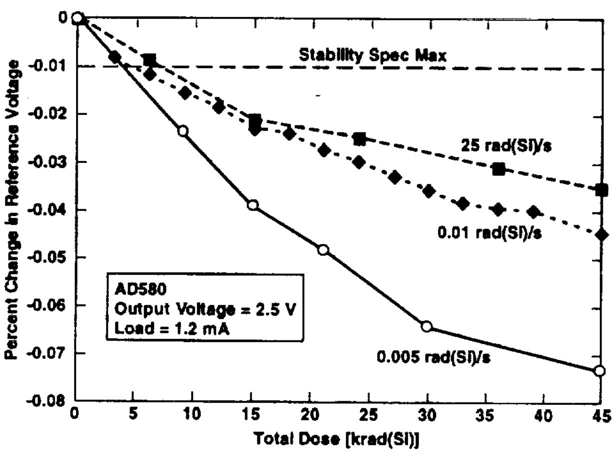

Figure 5. Degradation of the AD580 precision reference with cobalt-60 gamma rays at three different dose rates.

PROTON DAMAGE

Proton displacement damage can be important for some linear integrated circuits because of the very wide base region of lateral and substrate pnp transistors. Although only small differences occur between cobalt-60 and proton test results (at equivalent total dose levels) for many circuits, there are important exceptions [9,10]. Circuits that use substrate or lateral pnp transistors in critical regions, such as input or output transistors, are particularly affected. In some cases proton test results show factors of 2-4 more damage than gamma-ray tests because of the additional displacement damage from protons, which adds to the ionization damage. Neutron testing is of limited value in evaluating such parts because both ionization and displacement damage are important, and the different types of internal transistors are affected in different ways by the two damage mechanisms.

Figure 6 compares the degradation of a basic comparator with a substrate pnp transistor input stage when it is irradiated with protons and gamma rays at equivalent total dose levels. The parameter of interest is input bias current, which is inversely dependent on the gain of the input transistor. For this device, approximately four times as much damage occurs with protons. The increased damage is consistent with the damage constant for a wide-base transistor structure.

An even more surprising result was observed for a hardened operational amplifier, the RH1056. This device is manufactured with a special process that is modified to reduce the sensitivity of lateral and substrate pnp transistors to ionization damage. However, the basic design of these transistors is similar to that of unhardened commercial processes, and the pnp transistors are sensitive to displacement damage.

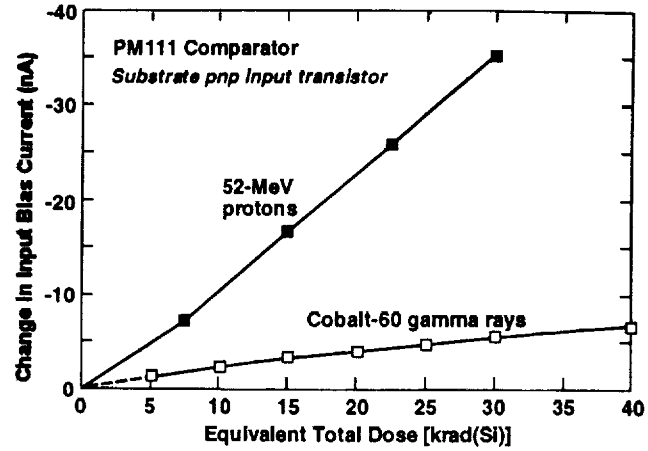

Figure 6. Degradation of the PM111 comparator from protons and gamma rays at equivalent total dose levels.

Figure 7 shows that when this part is tested with gamma rays, it functions to levels above 700 krad(Si), well beyond the 100 krad(Si) level specified by the manufacturer. Proton tests, however, provide markedly different results. Very large changes in offset voltage begin to occur at 50 krad(Si), and the part ceases to function at all at levels between 50 and 70 krad(Si). Such catastrophic failure is clearly a matter of great concern for applications of this part in earth-orbiting satellites for which protons are often the dominant source of radiation. No hint of such problems is provided by tests with gamma rays, even when tests are carried out at very high radiation levels.

A number of other device types are fabricated with the hardened process used by the RH1056. Although none of the others have been tested with protons, the results in Figure 7 suggest that other devices in the family may also fail at much lower levels due to displacement damage. This is clearly a concern for applications in MEO where devices are exposed to large proton fluences.

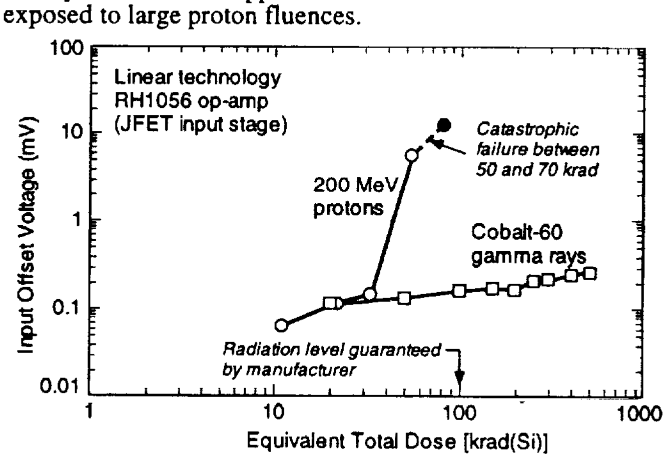

Figure 7. Comparison of the RH1056 response to protons and gamma rays at equivalent total dose levels.

LINEAR TRANSIENTS

Linear integrated circuits can also produce transients when they are exposed to protons and heavy ions [11-14]. The significance of these transients depends on the circuit application. In some cases they can have very important effects. For example, one application of a comparator in a hybrid power converter module results in dropouts of the output voltage for durations of about 10 ms each time that the comparator responds to a heavy-ion transient [15].

An example of transients from a comparator is shown in Figure 8. This device has an open-collector output. Transients caused the output to increase to the positive supply voltage even at a relatively low LET. The duration of the transients varies because the ions strike the device at random locations, producing a distribution of output pulses. At higher LET values, the results are similar but the pulses persist for much longer times.

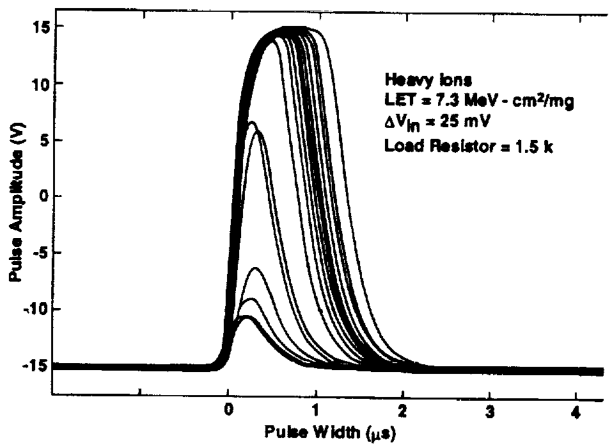

Figure 8. Example of the output transient from a comparator when it is irradiated with heavy ions.

Linear transients not only depend on the way that the circuit is used, but also on loading and input overdrive conditions. This creates a great deal of confusion in evaluating transients because results are often inconsistent between users. Input overdrive, output loading and the definition of the "trip point" where the instrumentation notes that a transient has occurred all influence the transient response of linear integrated circuits.

Transients from linear circuits are much more difficult to evaluate than digital circuits. Unlike digital circuits, there is a continuous *distribution* of pulse width and amplitude when linear devices respond to transients, even when tests are done at an accelerator with a single ion type (constant LET). Figure 9 shows the results of several transients for a PM139 comparator device, taken during a single test run with an LET of 7.3 MeV-cm^2/mg. The distribution of pulse widths is due to the reduced internal charge from ions striking regions somewhat beyond the most sensitive regions of critical transistors as well as the fact that many different internal transistors can affect the device, with differing responses [11].

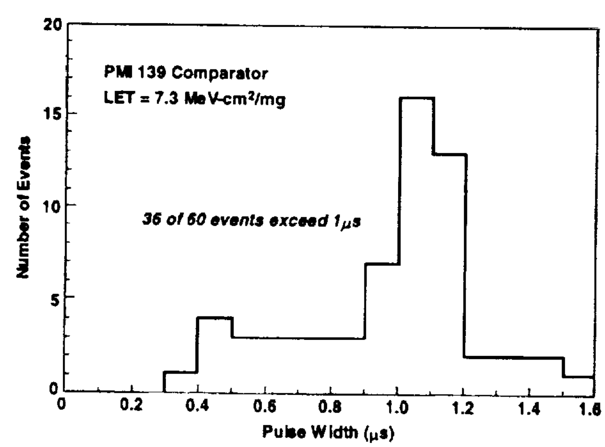

Figure 9. Distribution of pulse widths for a PM139 comparator when a series of responses are observed during a single test run with one ion type.

A similar distribution can be provided for pulse amplitude, but it is important to recognize that both the amplitude and width can affect the way that circuits respond to such transients. One way to deal with this issue is to provide statistical data about the pulse distribution at each LET.

Conclusions

This paper has discussed key radiation phenomena for linear integrated circuits, which have to be characterized and controlled more carefully than typical digital circuits. Although special hardened circuits are available, most systems rely heavily on linear devices produced by commercial technologies because of the wide range of devices that are available and the much lower cost. Most circuits are characterized with gamma rays at high dose rate, and markedly different results can occur, even for hardened devices, when radiation tests are done at low dose rates.

The main issues for future systems are in understanding how innovative, new linear designs are affected by the complex radiation phenomena that occur in these technologies, including the important problem of displacement damage. Low power devices and circuits with high-precision specifications are likely to continue to be weak spots in space system design. Transients in linear circuits from heavy ions and protons can also be important, depending on circuit applications.

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